

外加能量辅助搅拌摩擦焊技术的研究进展

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摘要: 搅拌摩擦焊已经成为材料成形领域主要的固相连接工艺技术。在简要回顾搅拌摩擦焊及其衍生焊接技术研发现状的基础上, 综述了近年来国内外开展的第二能量辅助搅拌摩擦焊的研究现状, 主要包括激光、电弧、感应、电流、超声等能量辅助搅拌摩擦焊技术。进而着重综述了超声振动辅助搅拌摩擦焊的研究进展, 介绍了目前出现的3种超声振动在搅拌摩擦焊中的施加方式。最后, 对外加能量辅助搅拌摩擦焊下一步的研发方向进行了展望。

关键词: 搅拌摩擦焊; 能量辅助; 激光; 电弧; 感应; 电流; 超声

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Research Progress of Secondary Energy Assisted Friction Stir Welding

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ABSTRACT: Friction stir welding (FSW) has become an important solid-state joining technology in materials forming field. This article first summarizes the development history of FSW and its variants briefly, and then reviews the research status of secondary energy assisted FSW developed in recent years, including laser, arc, induction, electric current and ultrasonic energy assisted FSW techniques. Further, the research progress of ultrasonic assisted FSW is reviewed emphatically. Three methods of utilizing ultrasonic energy in FSW are introduced in detail. At last, the outlook of the main development tendency of secondary energy assisted FSW is given.

KEY WORDS: friction stir welding; secondary energy; laser; arc; induction; electric current; ultrasonic

搅拌摩擦焊(Friction stir welding, FSW)已经在航空航天、轨道交通、船舶、汽车、军工等制造领域取得了应用^[1-4]。作为一种新型的固相连接技术, 其在焊接低熔点高性能轻金属材料(铝合金和镁合金等)时, 能够避免传统熔焊方法容易引起的气孔、裂纹等焊接缺陷, 具有接头质量高、焊接变形小和焊接过程绿色环保等优点^[5-7]。近年来, 随着搅拌摩擦焊技术的快速发展, 高熔点材料(钛合金、铁基合金、镍基合金等)

的搅拌摩擦焊接也越来越受到重视^[8-12]。然而, 常规搅拌摩擦焊主要依靠搅拌头与工件之间的摩擦产热和材料塑性变形功产热来软化待焊区材料并形成连接, 焊接时需要施加很大的轴向压力和旋转扭矩才能产生足够的热量和软化, 从而造成焊接载荷(包括轴向压力、旋转扭矩及前进阻力)大、工艺柔性差、装夹要求严、设备庞大、搅拌头磨损(甚至折断)等问题, 同时也限制了焊接速度的进一步提高, 影响了焊接效

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率^[13-16]。如果轴向压力不够大或者焊接速度超过一定值,会导致产热不足,造成材料的塑性流动性变差,难以获得优异的焊缝成形和接头性能。为了解决这些问题,研究者试图通过优化焊接工艺参数和改进搅拌头的设计^[13,16-21]来改善材料流动和产热,减小搅拌头磨损,但是效果有限。另一种思路是通过施加辅助能量来协助软化待焊材料。随着时间的推移,先后出现了激光、电弧、感应、电流、超声等能量辅助搅拌摩擦焊方法^[53-75, 80-98]。根据辅助能量的类型,大致可以将其划分为热能辅助搅拌摩擦焊(如激光、电弧、感应、电流等)和机械能辅助搅拌摩擦焊(如超声振动)。文中首先简要回顾搅拌摩擦焊及其衍生的焊接技术的发展现状,然后详细综述外加能量辅助搅拌摩擦焊的研究进展,并着重介绍3种超声振动辅助搅拌摩擦焊的工艺机理和工艺效果,最后对外加能量辅助搅拌摩擦焊的发展趋势进行展望。

1 搅拌摩擦焊技术的发展现状

搅拌摩擦焊技术诞生于1991年。经过20余年的发展,搅拌摩擦焊的相关技术和工艺理论日臻完善。人们已经认识到,搅拌摩擦焊是一个热-力耦合的塑性变形加工工艺^[5]。如图1所示,一个带有搅拌针和轴肩的高速旋转的搅拌头被向下的轴向力压入两块对接的工件接缝中,并沿着对接线行走。在搅拌针和轴肩的摩擦和挤压作用下,工件材料局部被加热至塑性流动状态,并随着搅拌头的旋转发生迁移,从而在搅拌头经过之后形成可靠的连接。由于搅拌头的旋转和移动,在焊缝中心线两侧材料流动呈现出明显的差异,为了区分这种差异,将旋转方向的切向与焊接移动方向一致的一侧称为前进侧(Advancing side, AS),而相反的一侧则被称为后退侧(Retreating side, RS)。

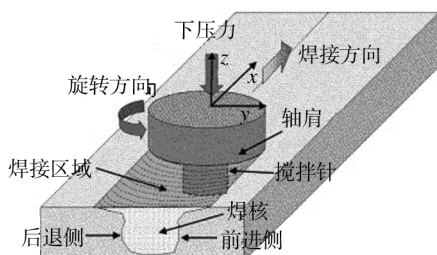
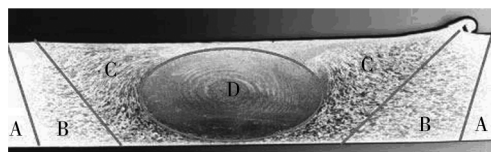


图1 搅拌摩擦焊接原理^[5]

Fig. 1 Schematic of FSW

在搅拌摩擦焊过程中,接头中的不同区域经历了

不同程度的塑性变形和热循环,形成了具有不同微观组织结构和性能的区域,在接头横截面上,其分布如图2所示。从中心向两侧依次是焊核区(weld nugget zone, WNZ)、热力影响区(thermo-mechanically affected zone, TMAZ)、热影响区(heat affected zone, HAZ)和母材(base metal, BM)。焊核区的材料经历了搅拌头的剧烈搅拌,晶粒发生严重破碎,在此过程中又发生了完全的动态再结晶,从而形成细小的等轴晶晶粒组织,一般具有良好的力学性能;热力影响区的材料经历了加热和塑性变形的共同影响,而塑性变形的程度远小于焊核区,因而该区域的晶粒组织发生了部分的动态回复和再结晶,呈现出具有明显变形痕迹的晶粒取向,力学性能一般稍差于焊核区;热影响区的材料仅仅是经历了焊接加热和冷却,晶粒在此过程中发生了粗化,晶粒内部的强化相也可能因此而溶解或长大,因而热影响区的力学性能一般都较差;母材既未发生塑性变形,也不受焊接热影响,力学性能一般不发生变化。



A母材; B热影响区; C热力影响区; D焊核区

图2 搅拌摩擦焊接头微观组织结构区域划分^[6]

Fig. 2 Microstructure of FSW joints

随着人们对搅拌摩擦焊认识的不断加深,一些基于搅拌摩擦焊基本原理的新技术也被不断研发出来。搅拌摩擦点焊(Friction Stir Spot Welding, FSSW)便是其中的一种^[22-24]。其原理与搅拌摩擦焊类似,即将高速旋转的搅拌头插入被焊的上下两层工件,利用摩擦产热和搅拌头高速旋转所引起的材料塑性流动形成接头。随着搅拌摩擦点焊技术的进一步发展,又演变出了回填式FSSW^[25-28]、摆动式FSSW^[29]、扫描式FSSW^[30]、无针式FSSW^[31-34](也被称为流动摩擦点焊)等多种点焊新技术。回填式FSSW通过起始阶段材料的吸入和结束阶段材料的压填而得到完整无匙孔的焊点。摆动式FSSW中搅拌头以一定距离为半径,绕搅拌头夹持端摆动一定角度来实现点焊,从而消除焊接中常见的界面畸变现象,并增加有效连接宽度。扫描式FSSW是指搅拌头在旋转的同时并以一定的运动轨迹进行移动,这样可以增大焊点截面积,提高接头力学性能。无针式FSSW(流动摩擦点焊)则类似于搅拌摩擦加工(Friction Stir Processing,

FSP),通过特殊设计的轴肩压入工件并旋转来带动上下两层工件材料的塑性流动,形成焊点。值得一提的是,上述无针式 FSSW 的搅拌头设计也可用于正常的搅拌摩擦焊连接^[35]。

双轴肩搅拌摩擦焊(Bobbin Tool Friction Stir Welding)也是一种新型的 FSW 焊接技术^[36-38]。它拥有上下两个轴肩并通过搅拌针相连,焊接时上下两个轴肩分别与工件的上下表面相接触,并形成相互支撑。其优点是不需要额外的背部垫板即可进行搅拌摩擦焊接,可解决一些中空结构和不便施加背部支撑的结构的搅拌摩擦焊接问题,并从根本上消除未焊透等根部缺陷,是对常规搅拌摩擦焊的有力补充。

差速搅拌摩擦焊^[39-52]也是对常规搅拌摩擦焊的进一步发展,通过特殊的传动机构设计,实现轴肩与搅拌针的旋转速度和旋转方向的独立控制,即可根据需要控制其焊接热输入。在差速搅拌摩擦焊中,当轴肩和搅拌针旋转方向相同时,即为同向差速搅拌摩擦焊^[41-42],当轴肩转速为零时,即为静止轴肩搅拌摩擦焊^[39,43-49],当轴肩和搅拌针旋转方向相反时,即为逆向差速搅拌摩擦焊^[50-52]。其中静止轴肩搅拌摩擦焊又可以用于特殊场合,如角焊缝的搅拌摩擦焊接^[47]和旨在降低焊接载荷的高转速搅拌摩擦焊(转速超过 10000 r/min)^[48-49]。在角焊缝的搅拌摩擦焊接中,通过设计特殊的轴肩形状,使轴肩与工件的两个直角面紧密切合,并在焊接过程中不旋转,即可防止轴肩破坏工件和材料被挤出,形成无缺陷的角焊缝接头。在旨在降低焊接载荷的高转速搅拌摩擦焊中,静止轴肩的引入能够有效地减小孔洞、飞边等缺陷,使焊接过程保持稳定。逆向差速搅拌摩擦焊工件受到的来自搅拌针和轴肩旋转的扭矩还可以相互抵消一部分,使工件装夹变得更加容易。

复合搅拌摩擦焊技术借鉴了其他复合焊接如激光-MIG 复合焊、激光-TIG 复合焊等的设计思路,利用其他的小功率辅助能量促进搅拌摩擦焊接过程中的材料软化和塑性流动,从而降低焊接载荷、减小搅拌头磨损、提高焊接速度,甚至实现常规搅拌摩擦焊难以焊接的高熔点材料的同种或异种材料搅拌摩擦焊接,达到“1+1>2”的目的。常见的搅拌摩擦焊辅助能源有激光、电弧、感应、电流、超声等。

2 热能辅助搅拌摩擦焊技术的研究现状

在复合搅拌摩擦焊技术中,绝大多数是通过使用额外的加热装置在焊接时对工件待焊区域进行局部

预热,然后再进行常规的搅拌摩擦焊接。辅助热源的引入可以提高焊接温升速率,降低材料塑性变形抗力,减小搅拌头磨损等。常见的热源形式主要有激光、电弧、感应加热和电阻热等。

2.1 激光辅助搅拌摩擦焊

Kohn 等人^[53]于 2002 年率先提出了激光辅助搅拌摩擦焊(Laser-assisted friction stir welding, LAFSW)。其原理如图 3 所示,激光束被精确地作用在搅拌头前方的待焊工件局部进行预热,然后再由搅拌头进行常规的搅拌摩擦焊接,形成固相接头。激光的精确预热能够软化待焊材料,使工件在焊接时受到的扭矩有所降低,这就降低了工件对焊接工装的要求;同时搅拌头所需的进给力也有减小,因此能够减轻搅拌头的磨损,提高焊接速度。

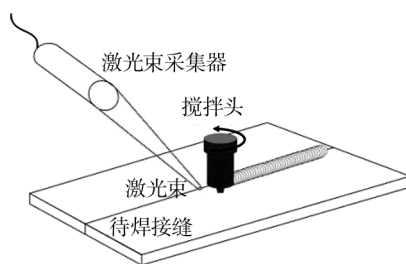


图3 激光辅助搅拌摩擦焊原理^[53]

Fig. 3 Schematic of laser assisted FSW

Kohn 等人^[53]、Zaeh 等人^[54]和 Casalino 等人^[55]研究了铝、镁等轻合金的 LAFSW 焊接,发现激光辅助能够明显消除焊缝内部缺陷,提高焊接速度,获得良好的接头力学性能。Sun 等^[56]研究了 S45C 钢板的 LAFSW 接头的微观组织和力学性能。研究发现当激光束聚焦在搅拌头前方 10 mm 的焊接线上时,焊接速度能够由常规的 400 mm/min 提高到 800 mm/min。当焊接速度低于 600 mm/min 时,能够避免焊缝中形成脆性的马氏体相。此外,当预热位置处于前进侧时,会显著降低搅拌头与工件之间的摩擦产热,而预热位置处于后退侧时,则会获得较高的热输入。此外,异种材料搅拌摩擦连接时可以利用激光集中加热熔点较高的一侧金属。Merklein 和 Giera^[57]的研究表明,使用激光预热能够提高钢/铝异种金属搅拌摩擦焊接的力学性能,原因是激光预热增强了材料流动,降低了金属间化合物层的脆性。Chang 等^[58]研究了在对接面上添加镍箔的铝/镁异种材料 LAFSW 焊接,发现激光辅助能够显著提高接头抗拉强度。原因是韧性较好的镍基金属间化合物相取代了原来的脆

性相 $\text{Al}_{12}\text{Mg}_{17}$, 而激光加热了镍箔, 改善了焊缝成形, 促进了镍基金属间化合物相的形成。

激光辅助搅拌摩擦焊也存在一些问题, 如激光在金属表面会发生反射, 造成了能源浪费。

2.2 电弧辅助搅拌摩擦焊

电弧辅助搅拌摩擦焊主要是指 TIG 电弧辅助搅拌摩擦焊和等离子弧辅助搅拌摩擦焊, 其原理与激光辅助搅拌摩擦焊类似, 如图 4 所示。先由焊枪在搅拌头前方不远处对工件局部进行预热, 然后再由搅拌头进行正常焊接。焊枪既可以是 TIG 焊枪, 也可以是等离子弧焊枪。

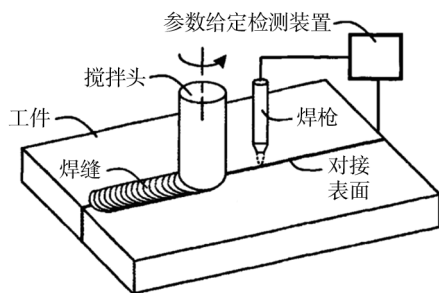


图4 电弧辅助搅拌摩擦焊原理^[60]

Fig.4 Schematic of arc assisted FSW

刘会杰等人^[59-60]率先采用了等离子弧作为辅助热源焊接了 2219-T6 铝合金, 发现在保证接头力学性能的前提下, 焊接速度能够成倍增加。然而, 由于双重热循环的影响, 焊核区沉淀相发生明显粗化, 成为接头最薄弱区。

Yaduwanshi 等人^[61]研究了 1100 铝合金等离子弧辅助搅拌摩擦焊过程中的焊接轴向力、热循环、峰值温度、冷却速率、接头力学性能和显微组织等, 发现焊核区的晶粒组织得到细化, 焊接轴向力显著降低, 接头力学性能有所提高。Bang 等人^[62-63]尝试采用 TIG 电弧辅助焊接不锈钢 (STS304)/铝合金 (Al6061) 和铝合金 (Al6061)/钛合金 (Ti-6% Al-4% V) 异种金属, 以期提高接头力学性能。TIG 电弧分别被用来在不锈钢和钛合金一侧加热工件, 所获接头的横向抗拉强度都超过了铝母材强度的 91%。分析认为这是由于电弧预热增强了材料的塑性流动, 在不锈钢与铝合金的连接中电弧预热还形成了局部退火, 使焊缝伸长率显著增大。

电弧辅助搅拌摩擦焊的缺点是强烈的弧光会干扰正常的搅拌摩擦焊接, 使工作环境变差, 弱化了常规搅拌摩擦焊绿色环保的优点。

2.3 感应加热辅助搅拌摩擦焊

Midling 等人^[64]在早期申请的专利中提出了采用感应加热作为辅助热源的搅拌摩擦焊技术。其原理如图 5 所示, 感应线圈安装在搅拌头前方并随着搅拌头向前移动。感应加热可以塑化待焊金属, 降低材料流变抗力, 改善焊接工艺效果。

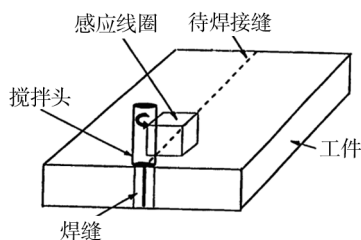


图5 感应热辅助搅拌摩擦焊原理^[64]

Fig.5 Schematic of induction heat assisted FSW

申志康等人^[65]研究了 Q235 钢的感应加热辅助搅拌摩擦焊接, 并对预热与否的焊缝显微组织、力学性能和显微硬度等进行了测试对比。发现感应加热预热可以提高钢的塑性, 降低搅拌头磨损, 提高搅拌头寿命; 但是预热同时也粗化了搅拌区的晶粒尺寸, 降低了接头的力学性能。Álvarez 等人^[66]研究了感应加热辅助搅拌摩擦焊接超级双相不锈钢 (GX2CrNiMoN26-7-4), 对比了常规焊接与感应加热辅助焊接条件下焊缝的微观组织结构和机械性能的变化。研究发现, 感应预热能够使焊接所需的轴向压力降低 31%, 或者在相同轴向压力下成倍地提高焊接速度。焊缝中没有发现 σ 相, 搅拌区的晶粒尺寸显著减小, 引起了接头平均硬度值和抗拉强度的提高, 铁素体比例介于 50%~70% 之间。

Sun 等人^[67]将高频感应加热应用于 S12C 钢板的搅拌摩擦焊点焊中, 工艺原理如图 6 所示。其研究发

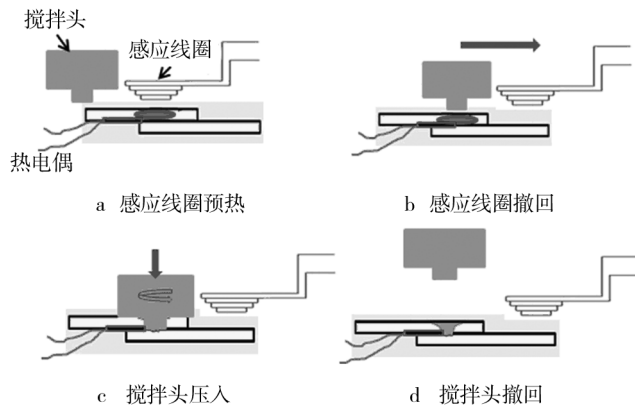


图6 感应加热辅助搅拌摩擦焊点焊工艺原理^[67]

Fig.6 Schematic of induction heat assisted FSSW

现,尽管高频感应加热预热增大了搅拌区的晶粒尺寸,但同时也增大了焊点的体积,即连接界面增大,从而增大了点焊接头的粘接强度;而且,搅拌头和工件之间的摩擦产热也因高频感应预热而减小。

感应加热的弊端在于不能对工件待焊局部进行精确加热,凡是能够产生感应电流的区域都会被加热,如夹具、搅拌头等。此外,感应加热对非导磁性材料的加热效率非常低,且不能加热非导电性材料。

2.4 电流辅助搅拌摩擦焊

电流辅助搅拌摩擦焊是指利用电流的焦耳热效应和所谓的“电塑性”来辅助软化待焊材料,提高搅拌摩擦焊过程中材料的塑性流动性。其中电流的运用非常灵活,衍生出了多种变体。

Luo 等人^[68-71]采用如图7所示的电流辅助搅拌摩擦焊方法,分别以搅拌头和工件端部作为两个电极,使电流流过工件内部进而产生电阻热。焊接了AZ31B 镁合金、7075 铝合金的对接接头,以及不锈钢2Cr13Mn9Ni4 和普通碳钢 Q235B 的搭接接头,发现电阻热细化了镁合金焊核区晶粒组织,提高了其显微硬度,增强了塑性变形。而对于铝合金,焊核区和热影响区的晶粒尺寸随着电流密度的增大而轻微增加。另外还指出电流辅助搅拌摩擦焊对于钢等高强合金的焊接有很大的应用潜力。Santos 等人^[73-74]改进了电流辅助搅拌摩擦焊,如图8所示。其在搅拌头的轴心增加一个铜芯,并在背部垫板上相应地增加一个铜键,使电流在工件中的分布更加集中,很好地解决了常规搅拌摩擦焊由于底部产热不足引起的未焊透等根部缺陷。

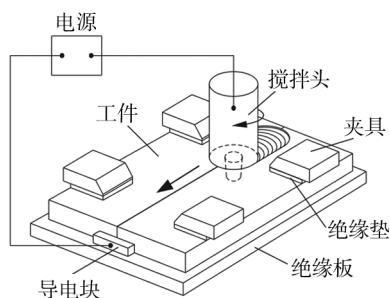


图7 电流辅助搅拌摩擦焊原理(电阻热)^[68-71]

Fig. 7 Schematic of electric current assisted FSW (Joule heat)

Liu 等人^[75]研发了如图9所示的电流辅助搅拌摩擦焊,两个直接施加在工件上的电极可以形成一个随搅拌头移动的电流场,而不需要搅拌头作为其中一个电极。其研究了电塑性(高密度电流引起的金属软

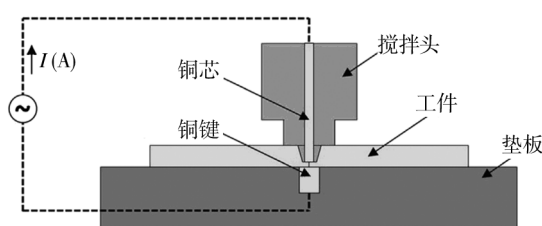


图8 改进的电流辅助搅拌摩擦焊原理(电阻热)^[73]

Fig. 8 Schematic of improved electric current assisted FSW (Joule heat)

化)对6061 铝合金和 TRIP780 钢异种金属连接时的影响。发现辅助电流能够显著减小焊接轴向力,并且当搅拌头转速较低或者搅拌头向铝侧偏移量较小时,这一现象更加明显。微观结构观察显示,在铝/铁界面上金属间化合物薄层的形成和微观上的互锁特点被增强,因而提高了接头质量。

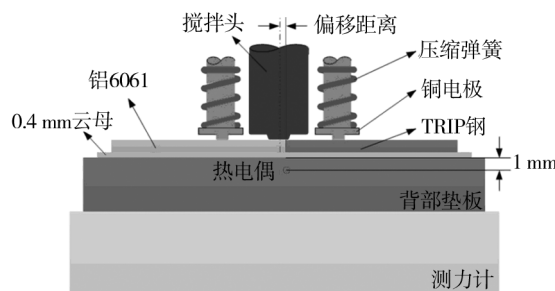


图9 电流辅助搅拌摩擦焊(电阻热和电塑性)^[75]

Fig. 9 Schematic of electric current assisted FSW (Joule heat and electro-plastic effect)

电流辅助搅拌摩擦焊存在的问题是:金属材料的导电性一般都较好,导致电流的热效率非常低,往往需要很大的电压^[71]或电流^[73]才能产生作用,即使是利用电塑性,所需电流强度仍然非常大(超过500 A^[75])。

此外,尽管辅助热源能够促进材料软化,但是也会导致工件材料经历双重的热循环,如果热源参数不当,会导致焊缝热影响区扩大,焊缝金属的强化相长大或溶解,从而降低了接头的力学性能,缩小了可用工艺参数的范围。

3 超声振动辅助搅拌摩擦焊的研究进展

超声振动作为一种机械能,具有频率高、方向性强和能量集中等特点。早在20世纪50年代,人们就发现超声振动能够降低金属材料塑性变形时的屈服

应力和流变应力,但是热作用并不明显。Langenecker^[79]在研究高纯度铝单晶拉伸时发现,在室温下对铝单晶施加一定能量密度的超声振动,其变形时所需的拉伸应力会显著降低,与加热至一定温度条件下的拉伸应力相当,如图10所示。当超声振动的能量密度达到 50 W/cm^2 时,其所需的拉伸应力几乎下降为0,与加热至 600°C 的条件相当。而在对不锈钢和铍的测试中发现,如要将拉伸应力降至“零”,所需的超声能量密度约为 $80 \sim 100 \text{ W/cm}^2$ 。类似的现象在锌、镉、铁、钛、钨等金属材料中也存在^[76-79]。

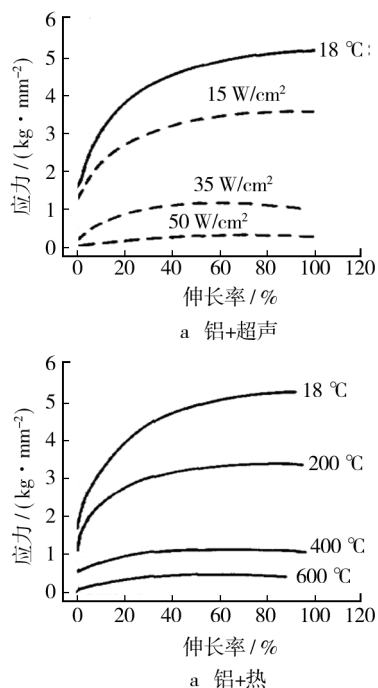


图10 单晶铝拉伸应力应变曲线(超声频率20 kHz)^[79]

Fig. 10 Stress vs. elongation for aluminum single crystals (ultrasonic frequency 20 kHz)

将超声振动引入搅拌摩擦焊,利用超声振动降低焊接区材料的屈服应力,提高其塑性流动性,从而降低焊接轴向压力和主轴转矩,减小搅拌头磨损,提高焊接速度,成了最近兴起的复合搅拌摩擦焊技术。目前主要有3种超声振动的施加方式,即从横向施加于搅拌头上、从轴向施加于搅拌头上以及直接施加在工件上。

3.1 超声振动从横向施加于搅拌头

Park等人^[80-82]将超声振动从横向施加于搅拌头上,研发了超声辅助搅拌摩擦焊工艺(Ultrasonic assisted FSW, UaFSW),其原理如图11所示。首先超声波发生器将市电转换为超声频的电信号,然后换能器

将其转化为超声频的机械振动,再经超声传递装置及振动耦合装置将纵向的超声振动传递至搅拌头。超声传递装置即为通常所说的变幅杆,起到聚焦超声能量、放大振幅的作用。振动耦合装置由两个对称的滚动轴承组成,并通过两根轴紧固在超声传递装置上,随其做同频率同方向的超声振动。滚动轴承的外圈再与搅拌头柱面紧密配合,其在搅拌头旋转的带动下做高速转动。这样,来自换能器的纵向的超声振动就变成搅拌头的横向振动,因此,搅拌头的运动状态即为横向的超声振动叠加在周向的旋转运动上,焊接时再由搅拌头将超声振动传递至待焊工件中。其进行的6061铝合金平板对接和1018钢平板对接工艺试验表明,UaFSW工艺不仅能够降低铝合金焊接阻力,提高焊接接头的力学性能,减小甚至消除焊缝成形缺陷,同时也能够减小钢材搅拌摩擦焊的轴向压力,提高焊接温度。

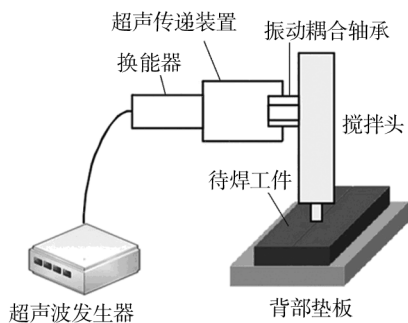


图11 超声振动从横向施加于搅拌头^[82]

Fig. 11 Schematic of superposing ultrasonic vibration on FSW tool in horizontal direction

Rostamiyan等人^[83]研究了6061铝合金超声振动辅助搅拌摩擦焊点焊(UaFSSW),其原理与UaFSW类似。研究表明超声振动能够显著提高搭接接头的抗剪切强度和显微硬度。Ahmadnia等人^[84]研究了UaFSW工艺参数对6061铝合金焊接接头的力学性能和摩擦特性的影响。其优化了超声功率、搅拌头转速、焊接速度和轴向压力以获得最优的接头抗拉强度和焊缝成形性,以及最小的表面粗糙度和滑动磨损率。结果表明超声功率对焊接接头的力学性能和摩擦特性都有非常重大且积极的影响。

应当指出,这种从横向施加超声振动的方式得到的振动效果一般,超声振动的能量在传递至待焊工件的过程中损失(包括超声传递装置自耗、耦合损失和搅拌头自耗等)较大,能量利用率较低。超声传递装置和振动耦合装置的设计也相对复杂,加工难度较大。

3.2 超声振动从轴向施加于搅拌头

贺地求等人^[85-89]提出了超声搅拌复合摩擦焊方法(Ultrasound Stir Compound Welding)。其原理如图12所示,将搅拌针与超声的换能器变幅杆集成为一体,这样搅拌针上会叠加轴向的超声振动,再以正常的搅拌摩擦焊程序进行焊接,从而将超声振动的能量导入到焊缝深层。超声振动能量的导入能够降低焊接流变的抵抗力,减小焊后残余应力,改善了焊缝组织,提高了焊缝强度,同时超声的加入还可以起到细化晶粒,改善金属宏观和微观偏析的效果^[85]。Amini等人^[90]采用了类似的原理设计了一体化的超声变幅杆和搅拌头,并进行了6061-T6铝合金的焊接工艺试验研究,结果表明超声振动降低了焊接载荷,提高了焊接温度。

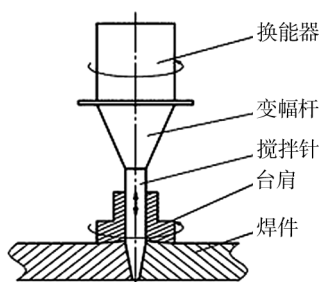


图12 超声振动从轴向施加于搅拌头^[85]

Fig. 12 Schematic of superposing ultrasonic vibration on FSW tool in axial direction

这种设计方法的优点是能够保证超声作用的部分位于搅拌区,超声能量能够作用于焊缝深层。但是在这种设计中,焊接时很大的轴向压力会对搅拌针的超声振动产生不利影响,这将影响超声的实际作用效果,目前相关的报道中仅限于薄板焊接^[85-90]。在将搅拌针和超声的换能器变幅杆连为一体时,需要采用相对复杂的安装机构,对搅拌摩擦焊机改动较大;因为其搅拌头的设计与常规不同,因而该系统所用搅拌头与通用的搅拌头不具有互换性。为了使超声振动系统工作在谐振频率上,需要针对不同厚度的工件制作不同的搅拌头以及与搅拌头相匹配的超声振动系统,增加了工艺的复杂性。

3.3 超声振动直接施加在工件上

武传松等人^[91-92]提出了直接将超声振动通过工具头施加在搅拌头前方的待焊工件上的工艺方法,并称之为超声振动强化搅拌摩擦焊(Ultrasonic vibration

enhanced FSW, UVeFSW),其原理如图13所示。超声波发生器传输的信号依次经过换能器、变幅杆和工具头,转变成超声频的机械振动,直接作用在搅拌头前方的待焊区域。

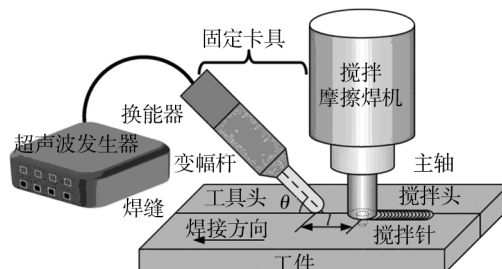


图13 超声振动强化搅拌摩擦焊原理^[92]

Fig. 13 Schematic of UVeFSW

Liu等人^[93-96]开展了6061和2024铝合金的超声振动强化搅拌摩擦焊工艺试验,发现施加超声能够改善焊缝表面成形效果,增大焊缝截面积,减小甚至消除焊缝内部缺陷,优化接头微观组织结构,提高接头力学性能和焊接速度。

在此基础上,Liu等人^[97-98]进一步开展了超声振动强化搅拌摩擦焊的材料流动试验。其将1060纯铝箔以不同的配置方式夹在基体材料之间,通过搅拌头“急停”技术和焊缝“切片”技术以及特殊设计的焊接行程来观察搅拌头周围材料的瞬态和准稳态流动。研究结果表明,超声振动的施加能够显著增加搅拌针周围变形材料的体积,提高搅拌区材料的流动速度以及应变和应变速率。

目前该技术正处在积极的研究中,存在的主要问题是进一步优化超声振动系统参数,争取更加显著的工艺效果;以及超声工具头作为一个消耗品,如何有效地保证其使用寿命。

4 结论与展望

搅拌摩擦焊技术因其相较于传统熔焊方法的独特优势,越来越多地受到人们的青睐。相信在倡导低碳经济的今天,搅拌摩擦焊技术一定会得到大的发展。通过综述搅拌摩擦焊接技术的发展现状和能量辅助搅拌摩擦焊的研究进展,可以得到以下结论。

1) 搅拌摩擦焊逐渐由最初的单一技术发展为全方位、多元化、综合性的焊接加工技术,为实际应用提供了更多选择,成为材料成形领域不可或缺的一分子。

2) 能量辅助搅拌摩擦焊技术作为对常规搅拌摩擦焊技术的延伸和补充,有效地拓宽了搅拌摩擦焊技术的应用领域。

3) 热能辅助搅拌摩擦焊受制于辅助热源的特性,其进一步发展将依赖于新的热源形式或者热源施加方式。

4) 与热能辅助搅拌摩擦焊相比,机械能(超声)辅助使搅拌摩擦焊能够避免双重热循环对焊接接头带来的不利影响,具有广阔的发展前景。

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